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Applications of process system engineering in palm-based biomass processing industry

Denny KS Ng and Rex TL Ng

Palm oil industry generates large amount of palm-based biomass (i.e., oil palm frond, oil palm trunk, empty fruit bunches, palm kernel shell, palm mesocarp fibre, palm kernel cake, and palm oil mill effluent) through harvesting, milling and replanting processes. With the increasing volume of global palm oil production, palm-based biomass utilisation is gaining significant attention as there are plenty opportunities and potentials to convert them into value-added products (e.g. dried long fibre, palm pallet, palm briquettes, and biofuels). In order to systematically synthesise, design and analyse the palm-based biomass processing facilities, Process System Engineering (PSE) is identified as the most promising engineering discipline to resolve the abovementioned issues. This paper focuses the review of the applications of PSE in palm-based biomass processing industry. This paper first presents potential utilisation of palm-based biomass. Applications of PSE (e.g. process modelling, process simulation, process synthesis, supply chain optimisation, and life cycle assessment) in palm-based biomass processing industry are then reviewed. Finally, future prospects and challenges of PSE in this industry are given.

Addresses
Department of Chemical and Environmental Engineering/Centre of Excellence for Green Technologies, The University of Nottingham, Malaysia Campus, Broga Road, Semenyih 43500, Selangor, Malaysia

Corresponding authors: Ng, Denny KS (Denny.Ng@nottingham.edu.my) and Ng, Rex TL (ngtonglip@gmail.com)

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Introduction

Oil palm, scientifically known as *Elaeis guineensis* Jacg., produces two distinct types of oils: crude palm oil from mesocarp and crude palm kernel oil from kernels [1]. Such oils possess excellent cooking properties and are widely used for food application (e.g. cooking oil, margarine, shortening, and cocoa butter) or non-food items (e.g. soap, cosmetics, and detergents). Based on statistics from United States Department of Agriculture, palm oil is the world largest vegetable oil production in 2012/2013, accounting for 55.29 million tonnes out of 159.64 million tonnes vegetable oils production [2]. Global palm oil production by country in 2012/2013 is illustrated in Figure 1. As shown, both Indonesia and Malaysia are world's largest producers accounting for 52% and 34% of world production, respectively.

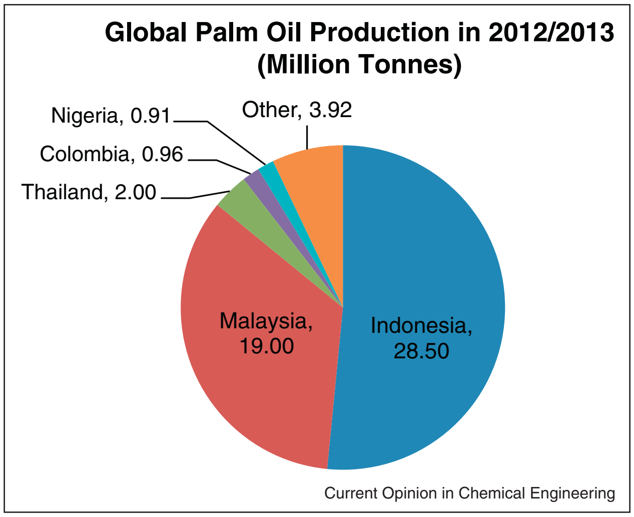
Throughout the milling process of oil palm fruits (fresh fruit bunches), various palm-based biomasses such as empty fruit bunches (EFBs), palm kernel shell (PKS), palm mesocarp fibre (PMF), palm kernel cake (PKC) and palm oil mill effluent (POME) are produced. According to Husain *et al.* [3], one tonne (1000 kg) of oil palm fruits generates of 210 kg of crude palm oil, 60–70 kg of palm kernel, 230 kg of EFB, 140–150 kg of PMF, 60–70 kg of PKS and 30–40 kg of PKC as well as 600 kg of POME. On the other hand, oil palm frond and oil palm trunk are also generated from the oil palm plantation. Generally, one hectare of oil palm plantation generates approximately 2.9 tonnes of trunks and 9.5 tonnes of fresh fronds stalk when replanting [4]. Based on the availability of the palm-based biomasses, there is a huge potential to convert those biomasses into high value products and create a billion dollar business model [4].

Palm-based biomass utilisation

In the current practice, palm-based biomasses are commonly utilised directly for different applications. For example, PKC can be used as feed ingredient for animal; while, PKS can be utilised as organic lightweight aggregate in concrete production [5]. In addition, palm-based biomasses can also be further converted into value-added products via physical, biological and thermochemical conversions [6••]. For instance, palm pellet, palm briquette, hybrid plywood and medium density fibreboard (MDF) can be produced via physical conversion [3,7–9]; compost, bioethanol, biogas, biopolymer, etc. can be produced via biological conversion [10–16] as well as syngas, bio-oil, phenolic compounds, etc. can be produced from thermochemical conversion [17–26]. A summary of the recent research works on palm-based biomass conversion technologies is presented in Table 1.

Note that some of the value-added products act as intermediates which can be further upgraded for other applications; for instance, biogas can be used as fuel in gas turbine, internal combustion engine, etc. after appropriate treatment to produce electricity and shaft works. Besides, bio-oil can be further upgraded to substitute

Figure 1



Global palm oil production in 2012/2013 [2].

Table 1

Recent research on palm oil-based biomass utilisation.

Category	Technology	Value-added product	References
Physical	Densification	Palm briquette	[3]
		Palm pellet	[7]
		Hybrid plywood	[8]
		MDF	[9]
Biological	Anaerobic digestion	Biogas	[10–12]
	Fermentation	Bioethanol	[13,14]
		Biopolymer	[14,15]
		Compost	[16]
Thermochemical	Gasification	Syngas	[17–19]
	Pyrolysis	Bio-oil	[20–23]
	Torrefaction	Torrefied biomass	[24]
	Liquefaction	Bio-oil	[25,26]

fuel oil or diesel in electricity generation, chemicals and transportation fuel [27,28••]. Syngas produced from biomass gasification can be used as feedstock for the production of biochemicals, such as dimethyl ether, Fischer Tropsch fuel and mixed alcohol [29]. Hydrogen produced from gasification and pyrolysis can also be used for heat and power application [30,31].

Applications of process system engineering in palm-based biomass processing industry

According to Grossmann and Westerberg [32], Process System Engineering (PSE) is defined as *the field that is concerned with the improvement of decision making processes for the creation and operation of the chemical supply chain. It deals with the discovery, design, manufacture and distribution of chemical products in the context of many conflicting goals*. It has moved away from the traditional concern with the understanding and development of systematic procedures for the design, control and operation of chemical process systems [33]. Grossmann [34••] concluded that product discovery and design, enterprise and supply chain optimisation, and global life cycle assessment (LCA) are likely to emerge as major research challenges in the PSE discipline. Most recently, PSE is further applied to biochemical processing industry (e.g. palm-based biomass processing industry, etc.) instead of conventional chemical industry. In this paper, applications of PSE in palm-based biomass processing industry are discussed in the following section.

Process modelling and simulation

The characteristics (e.g. moisture content) of the biomasses show significant effects on the overall biomass conversion process [31]. Thus, the operating conditions for biomass conversation technologies are difficult to be determined. Process modelling and simulation can be carried out to predict the outputs of the process based on the given condition. In addition, process simulation and modelling can be used to study the behaviour of the process at different condition without going through the time consuming and expensive repeated studies. Although process simulation and modelling provide such benefits, accuracy of the predicted results is always a questionable issue. Therefore, to provide accurate results from the process simulation and modelling, data extracted from experiments plays an important role to verify the results.

Various works on process modelling and simulation of biomass conversion technologies had been performed to study the effect of operating conditions towards value-added products. Inayat *et al.* [35•] developed a kinetic modelling for hydrogen enriched gas production in steam gasification of EFB integrated with *in situ* CO_2 capture via MATLAB. The effects of reaction temperature and steam/biomass ratio on hydrogen purity, yield and efficiency were studied based on reaction mechanisms and rates at given operating conditions and reactor [35•]. On the other hand, thermodynamic equilibrium modelling is more commonly used in process design as it has advantages in determining the maximum yield based on thermodynamic limit [36]. However, equilibrium chemical reactions are hardly achieved in actual case. Ng *et al.* [37] presented a modified thermodynamic equilibrium modelling approach with inclusion of correction factors in equilibrium constant of PKS gasification. The study shows that the predicted gas composition is very close to the actual experimental results [37]. Later, a generic approach of thermodynamic equilibrium modelling of fluidised bed gasifier for different biomass (bagasse, rice husk, coconut shell and PKS) based on actual experiment was developed [38]. Besides, process optimisation on maximum hydrogen production based on the developed model was performed [38]. Based on the optimised result, the syngas composition, operating temperature and equivalence ratio were predicted. Other than first principle modelling, combustion kinetics for palm fibre fuel and modelling of the heat transfer inside the biomass boiler were conducted via advanced process modelling approach which is computational fluid dynamics (CFD) [39]. Via CFD study, the hydrodynamic behaviour of fluid in the studied system can be easily determined. Based on the developed model, temperature profile in the boiler was obtained and improvements were suggested to improve the combustion in boiler [39].

On the other hand, process simulation tool (ASPEN PLUS) is widely used for simulation of biodiesel and bioethanol productions from crude palm oil, EFB and PMF [40•], downdraft gasification of fronds [41] and ethanol production from EFB [42]. Four different configurations of biodiesel and bioethanol productions from crude palm oil, EFB and PMF were simulated. Based on the simulated results [40•], the lowest energy consumption was shown in integrated process of the combined production of biodiesel and bioethanol using a distillation column for biodiesel purification compared to other configurations [40•]. The effect of operating conditions (zone temperature, operating pressure, air fuel ratio and moisture content) on syngas composition was studied based on ASPEN PLUS simulation [41]. Meanwhile, the comparison of experimental and simulated results on ethanol production via biological pathway was conducted [42]. Based on the reported results [42], ethanol yield from both experimental and simulated results were similar.

Process synthesis

Due to the rapid development of different biomass conversion technologies, the concept of integrated biorefinery which integrates multiple technologies as a whole had been proposed [43••]. Via the integration of multiple technologies, integrated biorefinery has more flexibility in products generation, self-sustained energy and lower overall energy consumption compared to technology that operates independently [43••,44]. Process synthesis is useful in determining the optimum pathways of integrated biorefineries that meet the design objectives. Systematic approaches for synthesis of palm-based integrated biorefineries had been proposed [45,46,47•]. Ng *et al.* [45] presented modular optimisation approach for simultaneous process synthesis, heat and power integration in an integrated palm oil-based biorefinery with existing palm oil mill. As reported in Ng *et al.* [45], modular optimisation breaks a complex optimisation model (i.e. process synthesis, heat and power integration) into few small models (white-box, grey-box and black-box models) to reduce the complexity of the model and computational efforts. Most recently, an integrated palm oil processing complex (POPC) that consists of palm oil mill, palm oil refinery, palm oil-based biorefinery and combine heat and power plant (CHP) on the same site was introduced [46]. Via the process integration among the processing facilities within POPC, the interaction of processing facilities (e.g. energy, power and material recovery within the complex) can be enhanced. In cases where the processing facilities are owned by multiple owners and each of them has its own targeted economic performance goal, industrial symbiosis concept was adapted [47•] to promote the integration between different processing facilities.

Note that most of the abovementioned works were focusing on synthesising processes in utilisation of palm-based biomass based on a single optimisation objective, which was maximised the economic performance. However, in order to develop a sustainable process system, environmental and social aspects should be taken into consideration. Kasivisvanathan *et al.* [48] adapted fuzzy optimisation approach for retrofitting palm oil mill into integrated biorefinery with consideration of both economic and environmental perspectives. In addition, the optimum result was further analysed with Pareto curve. Based on the analysis, it was proven that the optimum result was located on the Pareto curve [48]. Most recently, Ng *et al.* [49•] incorporated social aspects in process synthesis of a sustainable integrated biorefinery. Safety and health assessments were taken into consideration together with economic and environmental performances. To address all perspectives simultaneously during process synthesis, fuzzy optimisation was adapted to trade-off the objectives based on the predefined fuzzy limits of each objective [49•].

Process synthesis with uncertainties and operation issues

The availability and quality of palm-based biomass and product demands as well as fluctuation of raw material of product prices can affect the economic performance of the synthesised integrated biorefinery. Thus, other than steady state design, process synthesis with uncertainties should be considered in palm oil industry. Robust optimisation was adapted in synthesising integrated biorefinery with consideration of uncertainties on biomass supply and product demand as well as product cost [50]. Based on the probability of different scenarios, the average economic performance of the synthesised integrated biorefinery was determined [50]. In addition, robust optimisation also determined the design capacity of each process unit in integrated biorefineries during the early design stage. The design capacity of process units was determined based on the worst case scenario in order to meet the requirements in all scenarios [51].

On the other hand, once the design of integrated biorefinery is established, operation issues of the biorefinery need to be considered. Bottlenecks of the processes will always happen in the cases where the demand of output streams is increase or the stringency of emission limits

[52]. A systematic algebraic approach for identifying bottlenecks in linear continuous processes in CHP of palm oil-based biorefinery was presented by Tan *et al.* [52]. Based on the presented work, mass and energy balances were described in input-output matrix; fractional change in throughputs of process units was computed and process bottleneck was identified. Once the bottleneck was identified, various debottlenecking strategies can be implemented to cope with the changes. On the other hand, Kasivisvanathan *et al.* [53•] developed a systematic approach for determining optimal process adjustments as a result of partial inoperability. Based on developed approach, optimal operational responses were determined when process disruption occurred.

Supply chain optimisation

Greenhouse gases (GHG) emitted from transportation is one of the sources of carbon emissions [54]. Supply chain optimisation is needed to reduce the overall GHG emission, while secure the palm-based biomass and value-added products supplies. In order to minimise carbon footprint from transportation of palm-based biomass (EFB), Lam *et al.* [55] presented a mathematical optimisation model for the synthesis of regional bioenergy supply chain. The model was extended to robust linear programming (LP) and mixed-integer linear programming (MILP) models to overcome uncertainties such as EFB seasonality and shut down of plants [56]. Recently, a new conceptual green strategy for a systematic design of waste-to-energy supply chain had been proposed to encounter process synthesis of integrated biorefineries and supply chain of palm-based biomass and value-added products [57•]. A systematic approach of two-stage optimisation was developed; the 'macro-stage' focused on the overall supply and delivery of palm-based biomass and industrial waste; whilst, the 'micro-stage' involved the optimisation and design of palm oil-based biorefineries [57•].

Life cycle assessment (LCA) of palm-based biomass

Apart from process synthesis, design, modelling and simulation, LCA is also considered as one of the important aspects of PSE discipline. LCA is commonly used for environmental impacts assessment of entire life cycle of value-added product production. For example, LCA with the inclusion of different treatment options of EFB and POME had been conducted [58]. Based on the result, biogas generation showed lowest environmental impact amongst other options. However, co-composting provides a more reliable solution to improve environmental performance as research showed adverse impacts if there is fugitive biogas emissions in biogas generation [58]. In addition, LCA of palm biodiesel production with and without biogas capture from POME were investigated [59•]. As shown in the results, significant improvement of environmental impact was observed in the case where biogas is captured from POME in palm oil mill. Lim and Lee [60] then performed the LCA study of bioethanol processing from different palm-based biomass (e.g. EFB, PKS, PMF and fronds). Due to low conversion yield and energy-intensive bioethanol processing technology, results showed that the implementation of bioethanol processing in palm oil biodiesel processing plant would not provide significant energy and GHG emission benefits although it showed positive environmental impact [60]. On the other hand, the environmental impacts of bioethanol production, methane recovery, briquette production, CHP, composting, MDF production, and pulp and paper production were also analysed via LCA [61]. In this study [61], both scenarios of with and without considering the allocations of avoided products within system boundaries were investigated. As shown in the results [61], the technologies with least emission in scenarios of without and with considering the allocations of avoided products within system boundaries are composting and CHP plant, respectively.

Future prospective and challenges of PSE

As pointed out by Grossmann [34••], product discovery and design, enterprise and supply chain optimisation, and global life cycle assessment are the major research areas of PSE. As reported in the previous sections, it is noted that supply chain optimisation and LCA had been considered by the research community [54–56,57•, 58,59•,60,61]. In addition, conventional focus of PSE on process synthesis, design, optimisation and operation of palm-based biomass processing industry were addressed in various works [35•,37–39,40•,41,42,43••, 44–46,47•,48,49•,50–52,53•]. However, further improvement on the accuracy of process modelling, simulation and optimisation of palm-based biomass value chain should be considered. More process design and feedstock parameters (e.g. particle size, moisture content, and reactor size) can be included in process modelling and simulation in future works. When more design factors are taken into consideration in the process modelling and simulation, more realistic and accurate output prediction based on given operating conditions can be determined. In addition, flexible design of palm-based biomass processing facility which able to handle various uncertainties on biomass quality, availability, product demands, etc. should be considered in during early stage of design. This will provide larger margins in making process modifications as it involves lower costs at early stages compared to latter stages. Furthermore, LCA of the entire palm-based biomass processing industry should be conducted. Once the LCA is established, Life Cycle Optimisation (LCO) can be conducted to optimise the life cycle of the products with minimum environmental impact. In addition, introduction of social perspectives (e.g. employability of the community, public awareness and acceptability technologies enhancement) for the synthesis and design of palm-based biomass processing industry can also be taken into consideration in the future works.

On the other hand, product discovery and design for palm-based biomass remains as an important research gaps to be filled up. Molecular product design approaches, which were developed previously [62••,63,64] for conventional chemical products, can be extended for the development of biochemical products. Via molecular design approach, biochemicals that meet the customer attributes can be determined. Next, process design for converting palm-based biomass into the high value-added biochemical products is determined. Other than molecular design, reaction pathway synthesis and analysis to convert palm-based biomass into various products via different technologies or processing facilities can also be considered.

Conclusion

In this paper, reviews of palm-based biomass utilisation and conversion technologies (i.e. biological, physical and thermochemical) are presented. Later, applications of PSE in palm-based biomass processing industry are reviewed. As shown in the paper, various approaches for process modelling and simulation, optimisation, synthesis and design are studied by the research community. Based on the interests and past research results presented, the implementation of PSE on palm-based biomass processing industry possesses abundant potential for future perspectives. The challenges faced in this industry also represent opportunities of attractive research areas.

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